

# Behavior of Prestressing Steels after Fire

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## Summary

Even if a fire does not give rise to apparent damage in a prestressed structure, mechanical properties of materials as well as load distribution can be affected. A verification of residual load bearing capacity after fire is necessary to determine if the structure can be maintained in use. Mechanical properties of structural steels at high temperatures have been extensively studied. However, no attention has been paid to the behavior of steel wires after fire. This paper seeks to give a simplified estimation of the non-visible fire-induced damages produced in steel wires, with the hope that this information can be useful for engineers in the structural evaluation after a fire. Two aspects should be considered when assessing the security of the structures: The reduction of the prestressing loads due to the increment in the stress relaxation losses during the exposure to high temperatures and the permanent damage of the residual mechanical properties of steel wires produced by the fire.

**Keywords:** fire; prestressed concrete; structural steel; prestressing tendons; mechanical properties; structural safety.

## 1. Introduction

Following a fire, if no collapse happens, there is a possibility of fire-induced damage. Then, the question which unavoidably arises is if the structure is still safe; what the load bearing capacity of the structure is and how it has been affected by the fire. Appropriate knowledge of the behavior of construction materials after a fire is of major importance for answering these questions; For this end, the behavior of prestressing steel wires after a fire is the subject of this work. Measurements on loaded steel wires used for prestressed concrete during and after several simulated fires have been performed. This paper seeks to give a comprehensive and extensive explanation and a simplified estimation of the non-visible fire-induced damages produced in steel wires, with the hope that this information can be useful for engineers in the structural evaluation after a fire.

## 2. Experimental: Characterization of prestressing steel behavior after fire

A detailed study of the prestressing steel behavior was performed, examining the two principal aspects that could affect the performance of the structure after fire:

- The residual mechanical properties of the wires after fire: Extensive literature is available on the mechanical properties of structural steel at high temperatures. However no attention has been paid to the mechanical residual properties after fire. In this work, wires were subjected to a complete cycle of heating and cooling while loaded. Figure 1-a shows the variation of tensile strength at room temperature after fire, for the different maximum temperatures reached during the fire simulations.
- The stress relaxation losses produced during fire: Temperature has a great influence on the stress relaxation; an increment of temperature produces a large increase in stress relaxation losses and, consequently, the prestressed compressive load provided to concrete decreases. In Figure 1-b, an example of the time-stress relaxation losses curves obtained in this work is depicted as a function of temperature.

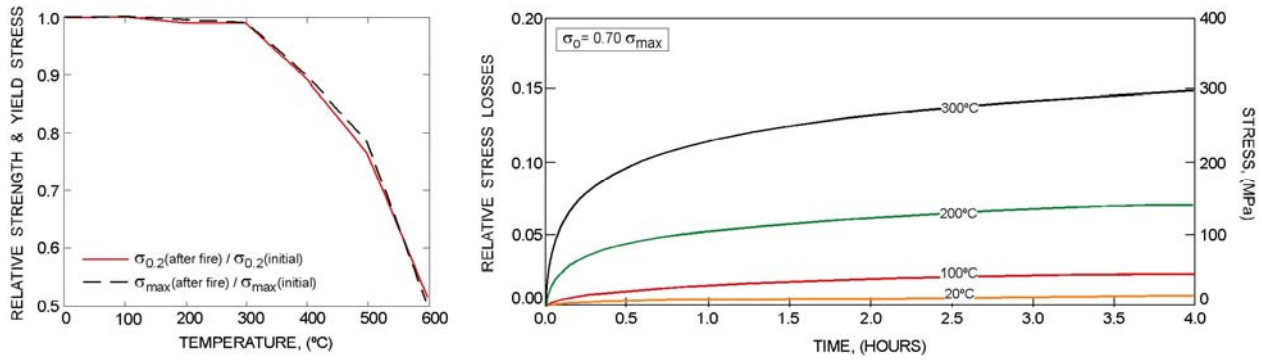


Fig. 1: a) Relative residual strength and yield stress at room temperature, after heating at different temperatures. b) Stress-relaxation losses (lost load/maximum load) as a function of temperature, for an initial stress of 70% of the wire strength.

### 3. Discussion: Estimation of fire-induced damage in prestressing steel

Figure 2 shows the experimental results of the evolution of the prestressed load before, during and after a simulated fire scenario. During the fire there is a significant reduction of the bearing load, as a consequence of the restrained dilatation and the increase of stress relaxation at high temperatures. When cooling, the part of this lost load due to the constrained dilatation is recovered, but not the stress relaxation losses. Thus, although the wire has successfully supported the fire without any visible damage, the prestressed load after fire has been considerable reduced, due to stress relaxation. Additionally, as the wire has suffered 500°C (see Fig. 1-a) the residual strength has been affected (20% less than the original value).

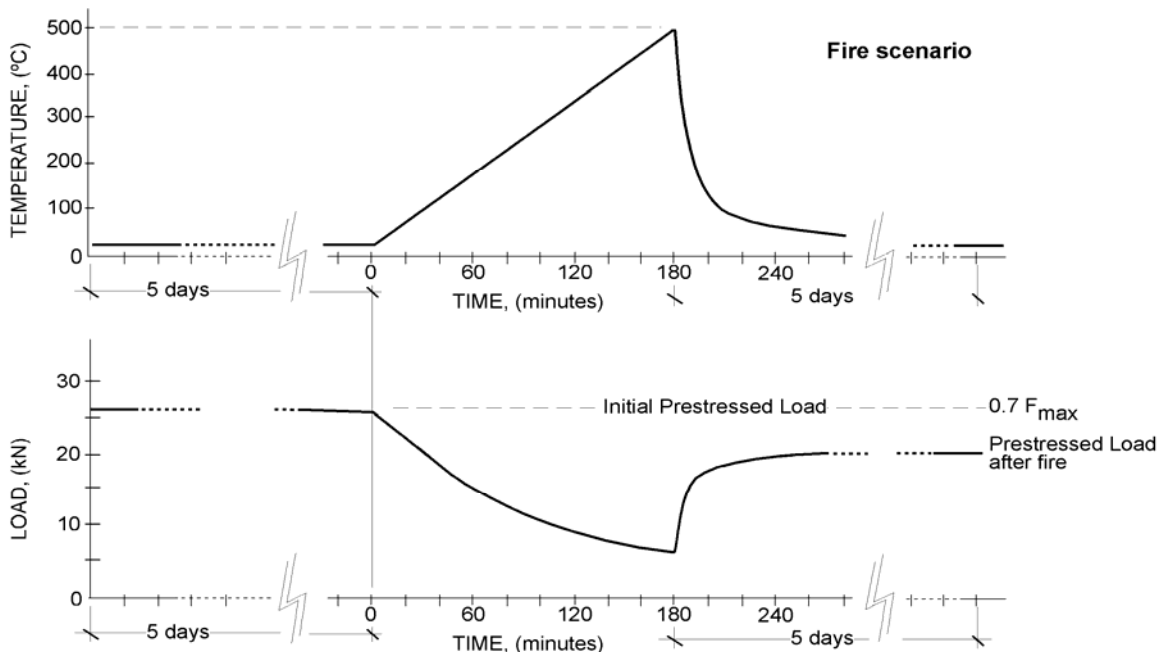


Fig. 2: Evolution of prestressed load before, during and after a fire scenario.

Fire safety should consider not only the performance of the structure during the fire but also the behavior of the structure after cooling. Even if a fire does not give rise to apparent damage in the prestressed structure, mechanical properties of materials as well as load distribution can be affected. The extent of damage in prestressing steels depends on the intensity and duration of the fire, the temperatures reached in the wires, as well as the load intensity they bear during a fire. A conservative estimation of the fire-induced damage can be obtained from the results presented in this work (as shown in Figure 1).

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## Summary

Even if a fire does not give rise to apparent damage in a prestressed structure, mechanical properties of materials as well as load distribution can be affected. A verification of residual load bearing capacity after fire is necessary to determine if the structure can be maintained in use. Mechanical properties of structural steels at high temperatures have been extensively studied. However, no attention has been paid to the behavior of steel wires after fire. This paper seeks to give a simplified estimation of the non-visible fire-induced damages produced in steel wires, with the hope that this information can be useful for engineers in the structural evaluation after a fire. Two aspects should be considered when assessing the security of the structures: The reduction of the prestressing loads due to the increment in the stress relaxation losses during the exposure to high temperatures and the permanent damage of the residual mechanical properties of steel wires produced by the fire.

**Keywords:** fire; prestressed concrete; structural steel; prestressing tendons; mechanical properties; structural safety.

## 1. Introduction

During a fire, high temperatures affect the performance of concrete structures due to the changes in the material properties and the strains and stresses generated by the dilatation. The fire behavior of construction materials plays an important role in the fire response of these structures, which has emerged as a controversial and even emotive subject to both the experts and the public.

The expected performance of a fire resistant structure is to support the design loads, even when exposed to a fire. A load bearing member fails to support the applied load when the load capacity is exceeded, with widespread structural failure possible if load transfer to adjoining elements is unsuccessfully. Investigation into the effects of fire has been conducted since more than fifty years ago. Today, fire design philosophy of prestressed concrete structures is based mainly on standardized procedures that ensure structural stability in a fire for a sufficient period of time to allow people to escape and the emergency services to extinguish the fire [1-8]. With this aim, a significant amount of experimental work on the characterization of the mechanical properties of construction materials at high temperatures has been carried out in the past decades [6-16]. However, no attention has been paid to the behaviour of materials after fire.

Following a fire, if no collapse happens, there is a possibility of fire-induced damage; this depends on the intensity and duration of the fire, as well as on the geometry, materials used in construction and loads they are withstanding. Thus, after a fire, the question which unavoidably arises is whether the structure should be replaced or if it is still possible to use it, either as it is or after some partial repairs. Before undertaking such repairs, an assessment of the load bearing capacity of the structure has to be carried out, even if it seems that no repairs are needed, since a misjudgement at this point can lead to unsafe situations. The financial aspect of this question is of course an important issue

and it may, in some cases, lead to the decision of demolition rather than repair of the remaining structure. In any event, the essential questions that have to be answered are if the structure is still safe, what the load bearing capacity of the structure is and how it has been affected by the fire. Appropriate knowledge of the behavior of construction materials after a fire is of major importance for answering these questions; For this end, the behavior of prestressing steel wires after a fire is the subject of this work.

Measurements on loaded steel wires used for prestressed concrete during and after several simulated fires have been performed, giving particular consideration to:

- The permanent deterioration of the material properties after a fire, particularly the strength and the yield stress.
- The reduction of the prestressing load after a fire, due to the increase of stress relaxation losses generated by the exposure to high temperatures.

This paper seeks to give a comprehensive and extensive explanation and a simplified estimation of the non-visible fire-induced damages produced in steel wires, with the hope that this information can be useful for engineers in the structural evaluation after a fire.

## **2. Experimental: Characterization of prestressing steel behavior**

When assessing the residual load bearing capacity of the structure after a fire, it is necessary to know the possible changes in their chemical and physical structure that could be reflected in a reduction of the mechanical properties after cooling down to ambient temperature. Extensive literature is available on the mechanical properties (strength, elastic limit and elastic modulus) of concrete and structural steel at high temperatures [1-13]. This information has been fundamental in predicting the behavior of the structure during fire, aiming at structural fire design. However little attention has been paid to the mechanical residual properties after fire [17], although they could be strongly affected by the maximum temperature reached. Knowledge of such changes seems to be important for predicting the load bearing capacity of the structure.

An additional aspect, not taken account until now, should not be forgotten when evaluating the structure after fire: the increment in the stress relaxation losses produced by high temperatures. By definition, stress relaxation refers to the decrease in stress at a constant deformation. In prestressed concrete structures, steel tendons in tension provide compressive stresses to the concrete. Throughout the life of the structure there should not be an appreciable loss of tension, because a reduction in prestressing loads would affect the structural safety [18,19]. Design codes place limits for keeping the relaxation losses within safe margins. Temperature has a great influence on the stress relaxation; an increment of temperature produces a large increase in stress relaxation losses. However, a literature survey has provided figures up to temperatures lower than 200°C [18,19].

Thus, a detailed study of the prestressing steel behavior was performed in this work, examining the two principal aspects that could affect the performance of the structure after fire: the residual mechanical properties of the wires after fire and the stress relaxation losses produced during fire. Commercial prestressing wires according to Standards (cold drawn and stress relieved steel wires, 5 mm diameter) were used in this research.

### **2.1 Stress relaxation losses at high temperatures (during fire)**

Stress losses are measured according to a standardized test (ASTM E328, ISO15630/3) and the figures should be provided by the manufacturer for the acceptance of the steel tendons; those with a figure of stress losses of less than 2.5% of the initial stress — after 1000 hours, at room temperature, when stressed at 0.70 of the tensile strength — are called “low relaxation” tendons and are those used in prestressing at present [18,19].

During a fire, the wire temperature increases and, depending on the boundary conditions, initial wire load can decrease due to the constrained dilatation. Since no results under such conditions were found in the literature, a detailed experimental study on the effects of temperature on the stress relaxation losses of the wires was performed. Stress relaxation tests at different temperatures and at different initial loads were carried out. The duration of the tests was four hours, longer than the

duration of the conservative fire scenarios proposed by standards. Temperatures studied were: 20, 100, 200, 300, 400, 500 and 600°C. Initial loads considered were: 10-30-50-70-90% of the tensile strength. Two tests were performed on each temperature-initial load couple.

In Figure 1, the time-stress relaxation losses curves are depicted as a function of temperature and initial loads. It can be seen that as temperature increases the stress relaxation losses increase significantly, and, consequently, the prestressed compressive load provided to concrete decreases. Clearly, this is a fact to be considered when assessing the fire-induced damage after cooling.

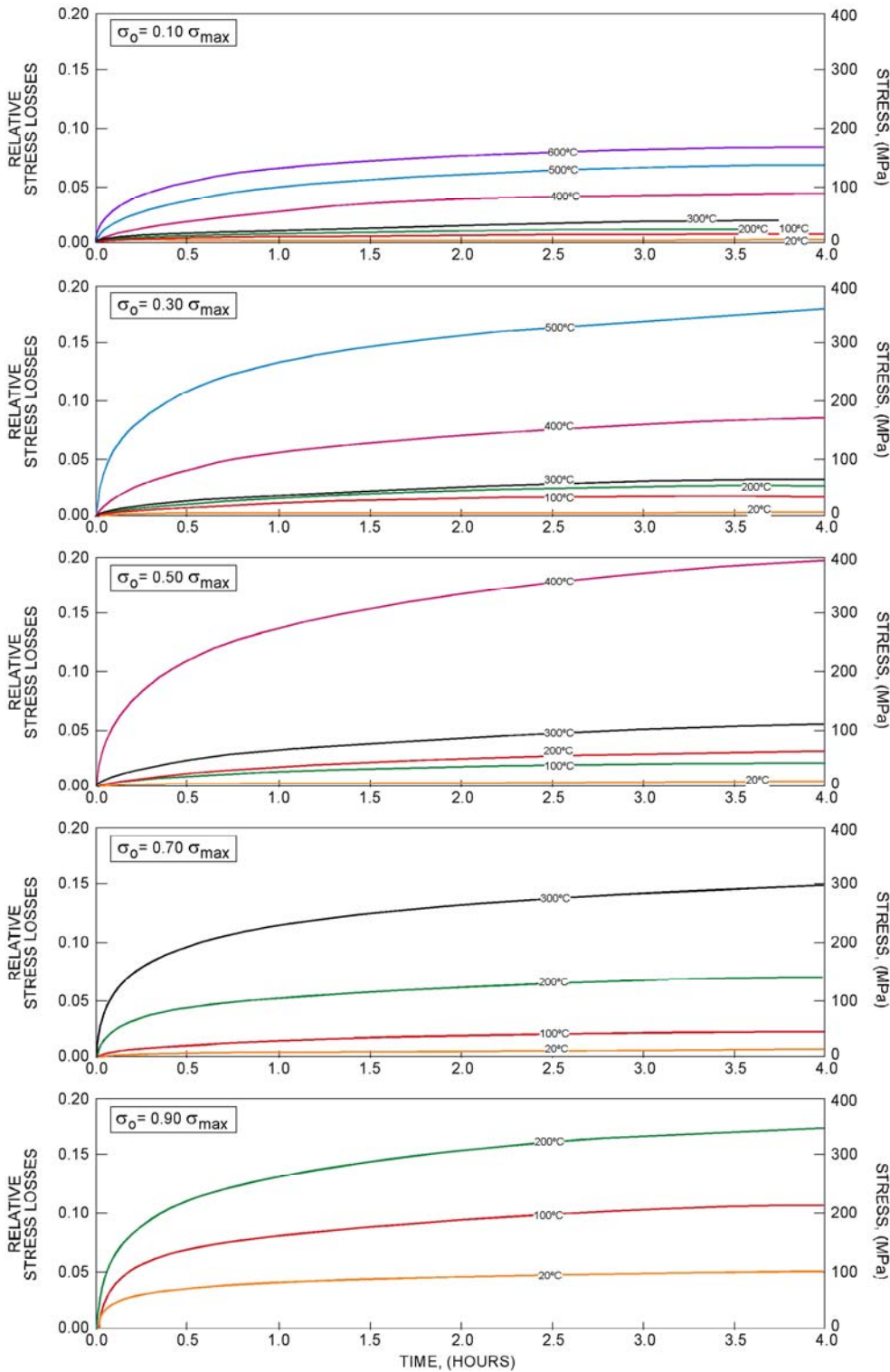


Fig. 1: Stress-relaxation losses (lost load/maximum load) as a function of temperature, for different initial stresses.



## 2.2 Residual mechanical behavior at room temperature (after a fire)

After a fire, even if no collapse happens and no effects can be visually seen in the structure, damage can be induced in the materials due to previous exposure to high temperatures. The term “residual” will be used here to indicate the properties that the prestressed steel exhibits after a complete cycle of heating and cooling.

Little attention has been paid in the literature to the mechanical behavior of prestressed wires after fire. Cabrita et al [17] analysed the effects of a thermal treatment on the mechanical properties of steel wires, showing that the strength of the wires could be affected. However, while this research did address many important aspects, it did not take into account the influence of load when heating the specimens, an aspect considered in this contribution.

In our work, to simulate the effects of fire, commercial prestressing wires were subjected to a complete cycle of heating and cooling (four hours), while loaded at 70% of their tensile strength. The effects of fire will depend upon the fire duration and the loading of the wire, in this case testing conditions are a conservative simulation since the duration of the fire is longer than the conservative ones proposed by standards, and the load is the maximum load experimented for the wires in service. Temperature was raised at a rate of 10°C/min and the different maximum temperatures studied were the same as the rest of this work: 20, 100, 200, 300, 400, 500 and 600°C. After cooling, tensile tests were performed to obtain the residual mechanical properties of the wires. Two tests were performed for each maximum temperature.

A result from [17] shows that for temperatures lower than 700°C, no differences were found in the residual properties after two distinct cooling processes: natural air cooling and cooling with a water jet. The first process was attempted to simulate the action of naturally extinguished fire. The second process was an attempt to simulate the action of the water used by fire fighters. In this work, only natural air cooling was studied.

Figure 2 shows the variation of the relative tensile strength and the relative yield stress, at room temperature, for the different maximum temperatures reached during the fire simulations, referring to their corresponding initial values before fire.

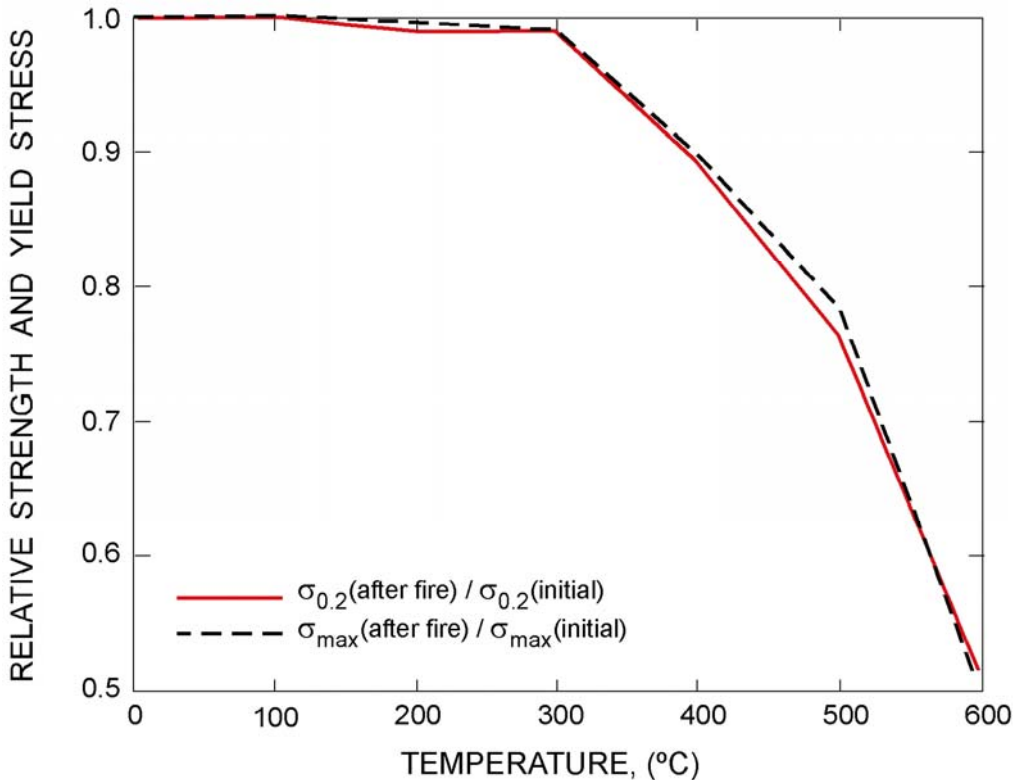


Fig. 2: Relative residual strength and relative residual yield stress at room temperature, after heating at different temperatures (for four hours).

The values of the residual tensile strength for the tested prestressing steel remain approximately constant up to temperatures around 300°C. If the wire suffers higher temperatures during fire, residual strength and the elastic limit are affected. Figure 2 can be helpful for estimation of residual load bearing capacity after fire. It should be noticed that an exact assessment of fire induced damage would require more variables, since it depends upon the duration and intensity of fire and prestressed load intensity. Figure 2 may be used as a simple and conservative estimation, since fire simulation utilized in this work was considered conservative.

### 3. Experimental simulation: Response of prestressing steel to a fire scenario

An example of a fire scenario has been simulated to represent the effects of a fire on the mechanical behavior of prestressing steel wires when the structure does not collapse, allowing the identification of the different aspects of the problem studied above.

Standards propose different nominal fires by defining the gas temperature during the fire duration. However, the key feature of the fire relevant to the prestressing steel behavior is the temperature-time curve endured by the material. Given that structural steel has a high thermal conductivity coefficient, when directly exposed to a fire it acquires immediately the fire temperature. However, as concrete surrounds steel wires and has low thermal conductivity, its thickness protects steel wires, delaying the values of temperature reached inside the structural elements. Standards provide curves to predict the temperature inside concrete elements during the nominal fires [1,15]. In Figure 3, the temperature evolution of steel wires for two different concrete covers is compared with the gas temperature curve proposed by standards.

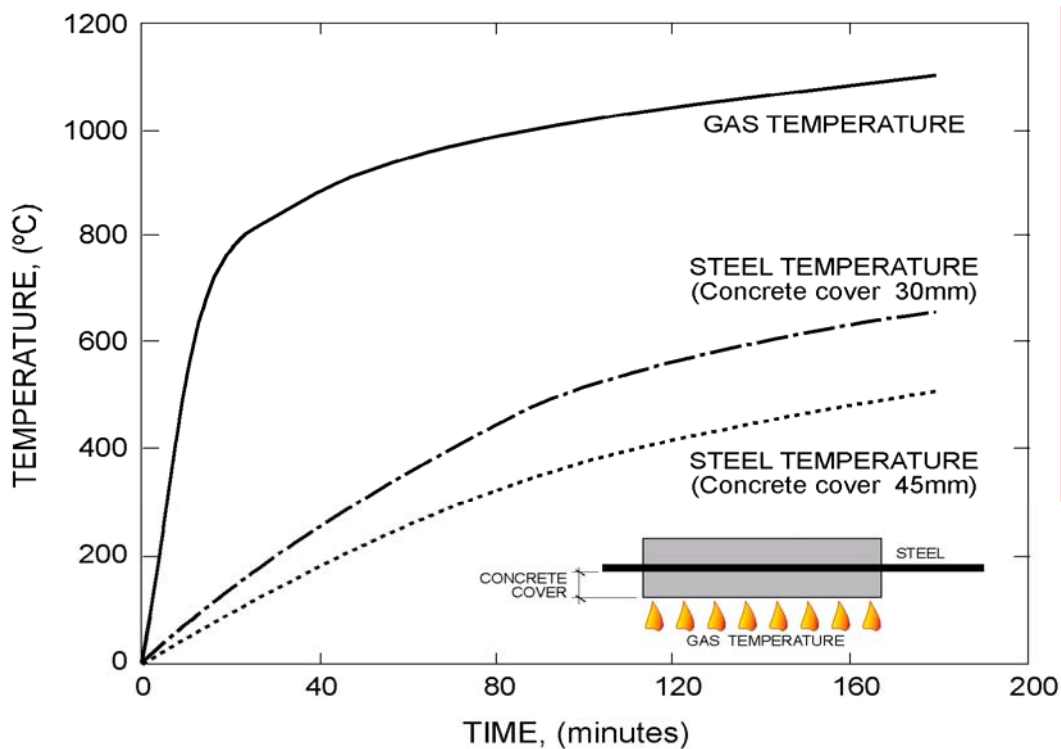


Fig. 3: Gas temperature in the Fire scenario proposed by EN 1991-1-2 [3]. Temperature as a function of time for two steel bars; one with a concrete cover of 30mm and another with 40mm.

In this work, an example of fire scenario was simulated following the next steps:

- A commercial prestressing steel wire is loaded at 20°C. The initial load has been 70% of the maximum load, the value proposed by Standards for the stress-relaxation tests. Usually, this is a conservative value; steel wires in most prestressed structures are loaded below this figure. The curve load-time is recorded continuously.

- Once the majority of the stress relaxation losses have occurred, after five days, the effects of fire are simulated using a furnace. The heating velocity is around  $3\text{ }^{\circ}\text{C}/\text{min}$  representing a typical temperature curve inside concrete elements during the nominal fires (see Figure 3). Maximum temperature,  $500\text{ }^{\circ}\text{C}$ , is reached at the end of the fire. The fire duration was three hours, longer than the fire duration proposed by the standards (two hours). After that, the furnace was turned off and left open so that the wire would slowly cool in air. The curve load-time is recorded continuously during the whole process.

- The test continues 5 more days at room temperature. Again, the curve load-time is continuously recorded.

An additional aspect should be considered to model the effects of fire: temperature produces a dilatation of the structural members which, in general, could not expand free due to the external constraints. The fire resistive properties of building components are measured and specified according to a common standard (ASTM E119). ASTM E119 [16] distinguishes between “restrained” and “unrestrained” assemblies. The term restrained means that thermal expansion of the specimen is restricted during the fire test. If a fire occurs beneath portion of a large structure, the heated portion will expand and push against the surrounded unheated portion. In turn, the unheated portion exerts compressive forces in the heated portion, altering the service load during the fire. In the case of unrestrained assemblies, the dilatation of the element is free. In this work, during the fire simulation the length of the specimen remains constant. This is a typical case of a restrained assembly, in which the service load would diminish during the heating because of the constrained dilatation.

Figure 4 shows the evolution of the prestressed load before, during and after the described fire scenario. It can be observed that during the fire there is a significant reduction of the bearing load, as a consequence of the constraint dilatation and the increase of stress relaxation at high temperatures. When cooling, the part of this lost load due to the constrained dilatation is recovered, but not the stress relaxation losses. Thus, although the wire has successfully supported the fire without any visible damage, the prestressed load after fire has been considerable reduced due to stress relaxation.

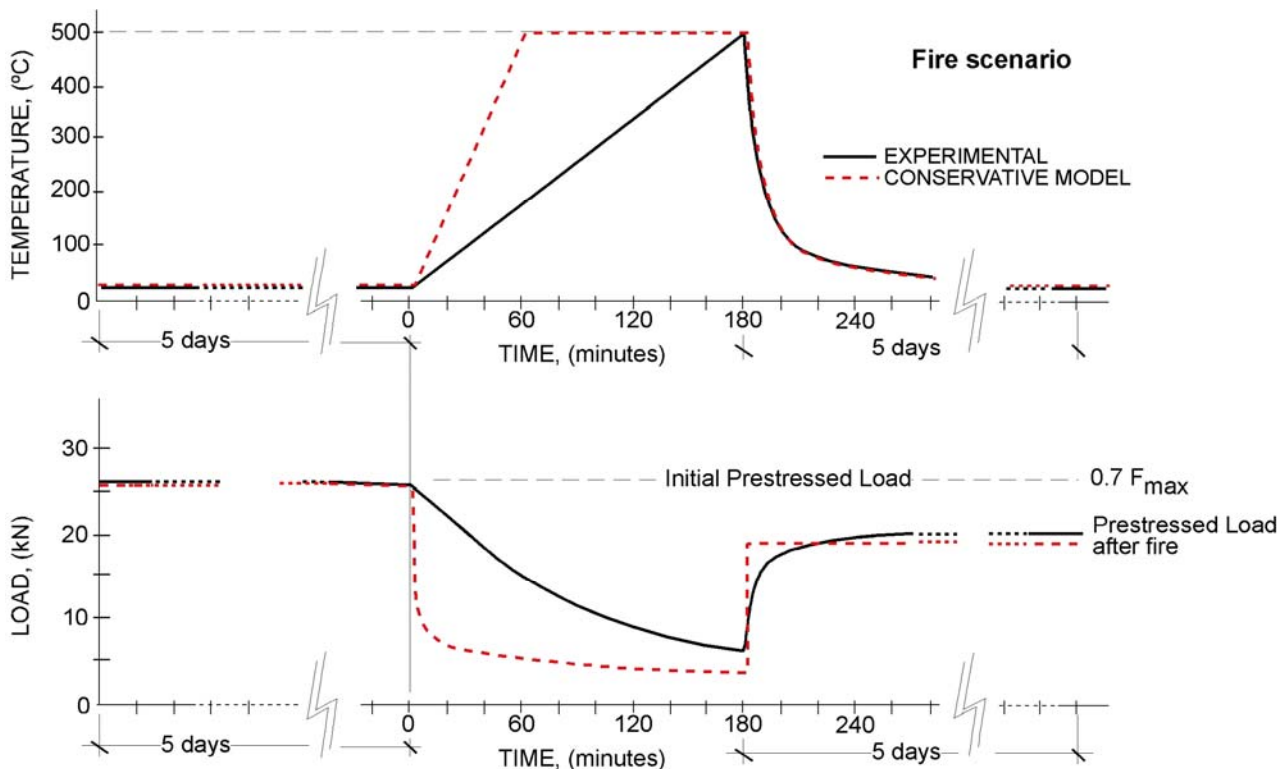


Fig. 4: Evolution of prestressed load before, during and after the fire scenario. Experimental measurements are compared with prediction of prestressed loads by a simplified and conservative method.



Assuming a simplified fire scenario where the maximum temperature has been reached soon and maintained along the duration of the fire, the curve time-load can be reproduced as the sum of three effects: the decrease of load as a consequence of restrained dilatation, equivalent to the recovering when cooling, and the stress relaxation losses curve at 500°C (obtained from data in Figure 1, in this case the initial load when reaching maximum temperature is 30% of the tensile strength due to the restrained dilatation). Looking at Figure 4, it is noticeable that the experimental results agree very well with the sum of these effects. This way, it is possible to obtain a conservative estimation of the loss in prestress load produced by a fire using the results presented in Figure 1.

Additionally, according to the results depicted in Figure 2, as the wire has suffered 500°C, the residual strength has been affected (20% less than the original value).

In summary, even the fire scenario has not produced visible damages, the strength of the wires as well as the prestressed load were significantly reduced, with the subsequent reduction of the residual load bearing capacity of the structure.

## 4. Conclusions

Fire safety should consider not only the performance of the structure during the fire but also the behavior of the structure after cooling. Even if a fire does not give rise to apparent damage in the prestressed structure, mechanical properties of materials as well as load distribution can be affected. A verification of residual load bearing capacity is necessary to determine if the structure can be maintained in use. Two aspects related to prestressing wires should be considered when assessing the security of the structures after fire:

- Reduction of the prestressing loads due to the increment in the stress relaxation losses during the exposure to high temperatures: Stress losses higher than 20% of the initial prestressed load can be produced. Curves of stress losses as a function of time, temperature and stress are obtained in this work (Figure 1) with the aim of helping in post-fire evaluation.
- Damage of the mechanical properties of steel wires produced by the exposure to high temperatures: Residual mechanical properties should be evaluated after a fire; it was shown that whenever temperature exceeds 300°C, some damage is produced on the material (Figure 2), with the subsequent reduction in the strength and the stress relaxation properties.

The extent of damage in prestressing steels depends on the intensity and duration of the fire, the temperatures reached in the wires, as well as the load intensity they bear during a fire. Some of these values are difficult to analyze; however, a conservative idea of the fire induced damage can be obtained from the results presented in this work (Figures 1 and 2).

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